Cost savings in wastewater treatment processes: the role of environmental and operational drivers.

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Abstract

In this study, 139 Tuscan Wastewater Treatment Plants (WWTPs) were analyzed with the aim of evaluating their efficiency and highlighting the main efficiency drivers, as well as distinguishing among wastewater features, WWTP technology, other features of WWTPs, output variables, and sludge disposal. From a methodological point of view, the proposed method includes an ordinary least squares analysis of total plant costs regressed on a set of 28 exogenous variables and a two-stage Data Envelopment Analysis model, where efficiency scores are obtained through weight restrictions. Moreover, the results of this study demonstrate that, with the exception of the "other features of WWTPs", all other clusters of variables exert a negative effect on cost savings; in other words, larger scale of operations and higher usage of the productive capacity (grouped as "other features of WWTPs") can improve cost efficiency.

Keywords: wastewater, wastewater treatment plants, efficiency, data envelopment analysis

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1. Introduction

Wastewater treatment (WWT) is an important link in the water cycle. Wastewater may be defined as liquid wastes discharged by residences, institutions, and commercial and industrial establishments and combined with groundwater, surface water, and storm water. Wastewater treatment methods are chosen based on the level of treatment that must be achieved to ensure the protection of public health and the environment, local conditions and needs, scientific knowledge and engineering judgment, and federal, state, and local regulations.

As highlighted by Molinos-Senante et al. (2014), in developed regions, virtually the entire population uses facilities for treating wastewater. However, even in these areas, two main challenges regarding wastewater treatment still exist: increasing the environmental sustainability of the process and minimizing the economic cost of operating these service operations. The expenditure on wastewater management and treatment in the EU-27 was approximately 0.60% of the Gross Domestic Product (GDP) (Eurostat 2012). In this context, the focus should be directed to the relevance of wastewater treatment for sustainability, equity, and well-being as well as to the need to assess best practices in order to improve the sector standards. Therefore, the use of tools and methodologies to assess and compare the efficiency of WWT processes is of great interest to companies and water agencies, because comparative analysis enables the identification of the strengths and weaknesses of each WWTP and introduces improvements to decrease costs and increase performance (Molinos-Senante et al., 2014).

This study aims to identify the main efficiency drivers of WWTPs, considering wastewater features, technology and other features of WWTPs, output variables, and sludge disposal. Data was collected from 139 WWTPs managed by a local water utility in Tuscany, in the center of Italy. To identify the efficiency drivers of wastewater treatment processes, the authors propose a novel approach which includes two paths: an ordinary least squares (OLS) analysis of total plant costs regressed on a set of 28 exogenous variables and a two-stage Data Envelopment Analysis model, where efficiency scores are obtained through weight restrictions. As far as the authors know, the present paper represents the first application of this kind of DEA model in the water sector. Thus, cost efficiency by the OLS analysis and a wider concept of efficiency, which referred not only to costs but also to the capability of each plant to remove pollutants from wastewater, were discussed. The identification of the environmental and operational variables affecting WWTP efficiency would provide utility managers with guidelines to build a benchmarking tool for the comparison of performance among plants. In fact, once efficiency was measured and a score was assigned to each unit, it could be corrected in the light of the effect exerted by exogenous variables, to obtain a “net score”. This would be strictly referred to the capability of a plant manager to purchase and combine the resources for wastewater treatment processes.

The empirical findings of this study confirmed the results of previous studies, especially those on the impacts of plant size on the efficiency and economies of scale. The quantity of pollutants removed is directly proportional to the costs incurred. Additional findings highlight the benefits obtained from the full usage of the plant capacity and from the option for a facility to be able to deviate from environmental standards at times. Advanced technologies, such as punctual aeration and sludge treatment on site, negatively affect cost efficiency, while no significant effects were demonstrated when technical efficiency was studied. Finally, the presence of industrial wastewater and the method of sludge disposal can influence total plant expenditure.

The remainder of the paper is organized as follows: Section 2 is devoted to a review of the existing literature, while Sections 3 and 4 present the data and the methodology, respectively. Section 5 presents and discusses the empirical results, while the final section contains a summary and some concluding remarks.

2. Literature review

The efficiency of water and wastewater treatment companies throughout the world has been investigated in many studies. Some of these studies focused on integrated firms that provided both water and wastewater services (Abbott et al. 2011; Abrate et al. (2016); Ashton 2000; da Cruz et al. 2013; Gill and Nema (2016); Guerrini et al. 2013; Guerrini and Romano 2014; Romano and Guerrini 2011; Saal and Parker 2001). There are several well-known benchmarking methodologies (Molinos-Senante et al. 2014) to study the efficiency of these services: ratios between outputs and inputs, total factor productivity, statistical techniques such as ordinary least squares (OLS), corrected ordinary least squares (COLS), stochastic frontier analysis (SFA), and Data Envelopment Analysis (DEA). As highlighted by Hernández-Sancho and Sala-Garrido (2009), the DEA model is a very useful tool to study the wastewater sector because it provides important information about the activity of WWTPs, allowing for the improvement of their global efficiency. Moreover, DEA can easily handle multiple input/output situations, even when they are expressed in different units, and it allows the aggregation of performance indicators into a single performance index (Sala-Garrido et al. 2011).

The literature on WWTP efficiency has grown in the last few years. Hsiao et al. (2007) and Oa et al. (2009) investigated the efficiency of treatment of wastewater from pig farms. In particular, using the DEA approach Hsiao et al. (2007) showed that most pig farms in Taiwan had decreasing returns to scale; moreover, larger pig farms usually had higher efficiency. In addition to the farm size, the number of sows on a farm, whether the farm sells shoats, and the years of education of the operator are among the other factors affecting its environmental efficiency. In Europe, the Valencia region in Spain has been investigated in depth recently. Hernández-Sancho and Sala-Garrido (2009) studied the efficiency of 338 plants using DEA. Each of the plants used secondary water treatment. The output of the model was the quantity of the contaminants removed, given by the sum of suspended solids (SS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD) removed (kilograms per year, on average). This quantity was calculated as the difference between the influent and effluent concentrations. Five model inputs were chosen: energy cost, labor cost, maintenance cost, waste management cost, and other costs (chemicals and amortization of capital costs). Hernández-Sancho and Sala-Garrido (2009) found that only 7.7% of the total number of plants were efficient and that the largest plants were more efficient than the smaller ones. Moreover, the most important differences between plants, in terms of efficiency, were the cost of maintenance and waste management.

Hernández-Sancho et al. (2011) used a sample of 177 WWTPs located in the same region of Spain (Valencia) that utilized the same process (i.e., prolonged aeration without elimination of nutrients). The goals of the study were to investigate the global efficiency of WWTPs and to analyze their energy efficiency and potential for energy savings. In their DEA model, they considered six inputs (energy, staff, reagents, maintenance, waste management, and other, all expressed in €/m^3) and two outputs (pollutants removed from wastewater in terms of suspended solids (SS) and organic matter measured as chemical oxygen demand (COD)). Both outputs were expressed in physical units (mg/L). The research findings confirmed that the number of plants operating efficiently was very low and that plant size, quantity of organic matter eliminated, and bioreactor aeration type were significant variables affecting the energy efficiency of WWTPs. The age of the plants was not a determining factor in energy consumption.

More recently, Molinos-Senante et al. (2014) analyzed 192 WWTPs located in the Valencia region, on the Mediterranean coast of Spain. In their DEA model, they used two outputs (suspended solids and organic matter measured as chemical oxygen demand, COD) and six inputs (staff costs, reagent cost, energy costs, waste management costs, maintenance cost, and other costs, which included office costs, laboratory costs, etc.). In the second stage of their analysis, they used non-parametric tests to explain the relationship of external factors with differences in efficiency scores and to identify the factors that require change to reduce operating costs of the WWTPs. Their empirical analysis showed that larger plants, in terms of volume of wastewater treated annually and plant capacity in terms of population equivalent (PE), were the most efficient, while medium-sized WWTPs were the least efficient. In particular, the cost of staff was the input most affected by the economies of scale. Moreover, they showed that the technologies used to treat the sewage sludge affected the efficiency of WWTPs, while the technology used for treating wastewater had no significant impact on efficiency. Furthermore, empirical results revealed that plants with the lowest energy consumption had the greatest efficiency. This means that reducing the carbon footprint contributes positively to improving the sustainability of WWTPs and provides significant economic savings. Finally, age of the plant (defined as the number of years since the WWTP was built or refurbished) had an impact on efficiency, because younger plants exhibited higher average efficiency, while sludge generation (expressed as kg of wet matter generated per cubic meter of treated water) did not affect the WWTP efficiency.

Sala-Garrido et al. (2011) analyzed 99 Spanish WWTPs, encompassing four alternative technologies: activated sludge, aerated lagoon, trickling filter, and rotating biological contactor. Their goal was to give utility managers scientific results from which to base informed decisions when selecting the most appropriate technology for new WWTPs. Their results indicate that the mean efficiency is relatively high and uniform across different technologies, but that techno-economic efficiency is optimal for plants operating with activated sludge, in comparison with the other technologies.

Regarding Italy, Fraquelli and Giandrone (2003) used a dataset obtained after a survey (edited in 1996 by Federgasacqua: the Italian Association of Gas and Water Public Utilities) provided to the managers of plants having a potential capacity above 10,000 equivalent inhabitants. The dataset comprises 103 observations about plants situated in 11 Italian regions, located predominantly in the center and north of Italy. In their cost function, they included the operations and maintenance costs, but excluded capital service costs (financing charges and depreciation) because of a lack of data. The costs are a function of the volume of wastewater treated (the hydraulic load on the plant), the basic qualities of the wastewater (concentration of pollutants and incidence of excess sludge), input prices (P), and a vector of technical dummy variables. The results showed that the volumes of treated water turn out to be the most significant variable in explaining the amount of cost. Moreover, the sludge level, the amount of pollution removed, and all parameters associated with input prices had a positive and significant correlation with costs. They found that vertical integration seems to produce significant economies of scope and that both the dehydration treatments investigated appear to increase expenses. In particular, the authors focused their attention on the existence of economies of scale. This included the fact that since the removed pollution load has a very significant role in explaining the variability of the costs, it is important to increase prevention measures and evaluate trade-offs between the cost of environmental protection, and the savings related to the reduction of pollutants in the liquid to be processed.

Despite the relevance of the investigation of WWTP efficiency for the economy, sustainability, equity, and well-being, to the best of our knowledge, there have been no other recent efficiency studies on wastewater treatment plants in Italy. This study was intended to fill a part of this gap by focusing on Tuscany, one of the most relevant Italian regions.

3. Data

Fraquelli and Giandrone (2003) highlighted that at the beginning of the new millennium, the situation of wastewater services in Italy was critical because the percentage of inhabitants served by the treatment services was low and there were a large number of small plants with questionable efficiency. Large-scale investments were needed and there was a lack of general infrastructure supporting the plants. In addition, to reduce the environmental impact of the wastewater treatment plants' activities, more attention was needed in the selection of the construction sites of the plants. Furthermore, while in some areas of the country advanced treatments were introduced, in other areas, wastewater treatment was still completely absent.

According to the Italian National Statistics Institute, in 2011 around 90% of the Italian population was served by WWTPs. In 2012, more than 18,000 WWTPs operated in the country, 1,200 in addition to the plants operated in 2008. As a matter of fact, in 2008 the number of currently operating WWTPs was less than the number to be constructed, and met only 59% of the national demand (Guerrini and Romano 2014). A similar situation exists in other countries. In Greece (Genius et al. 2005), inhabitants of the areas under consideration approved the construction of a wastewater treatment plant in their region and their willingness to pay was considerably higher than the amount needed for the implementation of the plant.

Our analysis is about WWTPs operating in Tuscany, a central region of Italy. The water resources authority in Tuscany (i.e., Autorità Idrica Toscana) is a public body representing all the Integrated Water Service managers in the area. Before 2012, Tuscany was divided into six "optimal areas" and for each area, there was a local authority called "Autorità di Ambito Territoriale Ottimale". Now, all the functions of the local authorities have been transferred to the Tuscan Water Authority and the optimal areas are now called "Conferenze Territoriali". In each "Conferenza Territoriale" there is a water utility company that is responsible for water supply and for the construction and maintenance of the necessary infrastructure.

Our data is from the 139 WTTPs located in Conferenza Territoriale Number 2. The Arno River is the most important river in this area and its estuary is located there. The area is also called "Basso Valdarno". We eliminated from our sample a very small WWTP, because of its incomparable size with others.

A data-model grid was defined considering these issues: 1) wastewater features, 2) WWTP technology, 3) other features of WWTPs, 4) output variables, and 5) method of sludge disposal.

The important constituents of concern in wastewater treatment are shown in Table 1, along with the most commonly used unit operations and processes.

Table 1. Principal constituents of wastewater with the unit operations and processes used to remove them (Tchobanoglous et al., 2003)

Constituent	Reason for importance	Unit operation or process
Suspended solids	Suspended solids can lead to the development of sludge deposits and anaerobic conditions when	Screening Grit removal Sedimentation

	untreated wastewater is discharged in the aquatic environment.	High-rate clarification Chemical precipitation Flotation
Biodegradable organics	Biodegradable organics are measured most commonly in terms of BOD (biochemical oxygen demand) and COD (chemical oxygen demand). If discharged untreated to the environment, their biological stabilization can lead to the depletion of natural oxygen resources and to the development of septic conditions.	Aerobic suspended growth variations Aerobic attached growth variations Anaerobic suspended growth variations Anaerobic attached growth variations Physical-chemical systems Chemical oxidation Advanced oxidation Membrane filtration
Pathogens	Communicable diseases can be transmitted by pathogenic organisms that may be present in wastewater.	Chlorine compounds Ozone Ultraviolet (UV) radiation
Nutrients	Both nitrogen (N) and phosphorus (P), along with carbon (C), are essential nutrients for growth. When discharged to the aquatic environment, these nutrients can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can also lead to the pollution of groundwater.	Nitrogen (N): - Suspended growth nitrification and denitrification variations - Attached growth nitrification and denitrification variations Phosphorus (P): - Chemical treatment - Biological phosphorus removal Nitrogen and Phosphorus (N-P): - Biological nutrient removal variations

In the empirical analysis, the wastewater features included the following items: percent wastewater coming from non-domestic customers, percent dilution of wastewater inflow, average concentration of BOD5, COD, N, and P. The WWTP technologies considered in this study include primary, secondary, and tertiary treatment; activated sludge treatment (Yes/No); type of aeration system (punctual/widespread); and presence of sludge treatment on site (Yes/No). This group of variables also included the sewerage system, which could either be combined or separated. In fact, wastewater is transported underground through pipes to treatment or disposal facilities. Older sewer systems (combined sewers) were designed to carry both sewage and surface runoff, whereas modern sewer systems are designed either to convey wastewater (sanitary sewers) or to drain surface runoff (storm sewers) and to keep these separate (Masotti 2011).

Among the other features of the WWTPs, six variables were considered: the distance between a WWTP and sludge treatment plant (when this treatment is not performed on site), plant capacity (PE), age of building, percent of production capacity used, length of sewers (km), and plant authorized to derogate some environmental standards (Yes/No).

The output variables were: the quantity of removed pollutants (kg) [distinguishing BOD5, COD, N, P, sludge, and other waste], the volume of treated water (m^3); the percentage of sludge dry matter obtained from sludge; and the percentage of controls not compliant with environmental standards. Finally, the method used for sludge disposal was determined and the percent of sludge disposed in landfills, used for composting plants, and used in agriculture was measured.

4. Methods

To analyze the WWTP efficiency and its drivers, two methods were employed. The first was based on the total cost of each WWTP, regressed on 28 operational and environmental variables, according to the following equation.

$$\mathrm{TC} = \beta^0 + \sum_{i=1}^{n} \beta^i \times x^i + \varepsilon$$

where TC represents the total cost incurred by each plant, β^0 is the intercept of the function, x^i is i$^{\mathrm{th}}$ of the 28 exogenous variables observed, β^i is the estimator for the i$^{\mathrm{th}}$ exogenous variable, and ε is the error term.

This preliminary Ordinary Least Squares (OLS) regression identified the main drivers of total cost, which include materials (reagents and other material), energy, staff, maintenance, depreciation and amortization, sludge transport, and disposal.

The second method involved a two-stage approach, based on the Data Envelopment Analysis (DEA) and regression analysis. DEA is a “data-oriented” non-parametric method for performance assessment and benchmarking of a set of entities called decision-making units (DMUs) which convert multiple inputs to multiple outputs (Cooper et al. 2011). For each DMU, an efficiency score is given by the ratio between the weighted sum of outputs and the weighted sum of inputs. The chosen system of weights is the most favorable to the evaluated DMU and the efficiency score is between '0' and '1'. From the seminal paper by Charnes et al. (1978), several different DEA models have been proposed over the last decades. In compliance with the existing literature on water efficiency (see Berg and Marques 2011; De Witte and Marques 2010, and references therein), we used an input-oriented DEA model with variable returns to scale (BCC model). In this context, a DMU is inefficient when it is possible to reduce all the inputs equi-proportionally and maintain (or even increase) the same level of outputs. Regarding the scale-assumption, each DMU was evaluated at the most favorable returns to scale assumption (Banker et al. 1984).

The DEA model we implemented considered three input variables and six output variables for the 139 DMUs analyzed. Even though the model complied with the simple "rule of thumb" proposed by Dyson et al. (2001), the resulting DEA model was not very discriminating. At the same time, the features of the dataset did not allow for aggregation among outputs, because this would lead to a meaningless model. To overcome these difficulties, we introduced output weight restrictions that reflected the rank of importance among some outputs. Regarding the introduction of weight restrictions in DEA models, the interested reader can see for all the contributions by Joro and Viitala (2004), Podinovski (2015), and Podinovski and Bouzdine-Chameeva (2013). In the present analysis, the chosen weight restrictions took into account some relevant aspects of the wastewater treatment process discussed with technicians at Acque SpA. Taking into account the weight restrictions in the DEA model, for each DMU k_0, we solved the following maximization problem:

$$
\begin{cases}
\max \quad \sum_{j=1}^{6} y_{jk^0}\ u_j + q_{k^0} \\
s.t \quad \sum_{i=1}^{3} x_{jk^0}\ w_i = 1 \\
\qquad -\sum_{i=1}^{3} x_{jk^0}\ w_i + \sum_{j=1}^{6} y_{jk^0}\ u_j + q_{k^0} \leq 0, k = 1, \dots, 138 \\
\qquad u_1 - u_5 \leq 0 \\
\qquad u_2 - u_1 \leq 0 \\
\qquad u_6 - u_4 \leq 0 \\
\qquad w_i \geq 0, u_i \geq 0, i = 1, \dots, 3, j = 1 \dots, 6
\end{cases}
$$

where

x_i denotes the ith input variable, i=1,…3; y_j denotes the jth output variable j=1,…6; w_i, u_j denote the weight assigned to the ith input and the jth output variable, respectively, and q_{k^0} is the variable related to the returns of scale.

According with the imposed weight restrictions, we assumed that the weight u_1, assigned to the first output, was not bigger than weight u_5, assigned to the fifth output. The other two weight restriction constraints can be interpreted in a similar way.

The obtained efficiency results were then regressed by considering the environmental and operational variables of our data set. Therefore, following the 'backward process', we detected the most relevant drivers affecting efficiency and then performed a reduced regression model, which included only those variables with statistical significance.

In the DEA model, we considered costs as input variables: more precisely, we aggregated costs in three input variables:

- x_1= material + energy costs,
- x_2= staff + maintenance costs, and
- x_3= sludge transport and disposal costs.

From the output side, we detected six fundamental variables:

- y_1= removed kg of COD, as a global output indicator for organic waste treatment,

- y_2= removed kg of Nitrogen (N),
- y_3= removed kg of Phosphorus (P),
- y_4= kg of produced sludge,
- y_5= volume of treated wastewater (m^3), and
- y_6= sludge obtained dry matter (%).

The output choice was driven by the necessity of constructing a model that could accurately represent the WWTP treatment processes. In this sense, we believe that any output aggregation would lead to a meaningless model. On the other hand, the high number of output variables led to a model which was not very discriminating. As mentioned before, by introducing weight restrictions in the original model, we combined the following conflicting necessities: having a realistic representation and increasing the discrimination of the model. More precisely we assumed that the treated wastewater must have a greater weight with respect to the kg of COD removed, which is in turn more important than the kg of N removed. Moreover, we wanted the produced sludge to have a greater weight than the dry matter.

5. Results and discussion

The 139 WWTPs were clustered by their different features: size, age, technology, and compliance with environmental law. Plants were distinguished as greater than 19,000 PE production capacity, smaller than 5,000 PE, and between these limits. Then, three clusters of plants with different ages were defined. The majority of plants are small and old or mature plants, more than 15 or 30 years old, respectively. Only 21 out of 139 WWTPs had a sludge treatment plant on site: among these, most were big or medium plants, while only 3% of the small WWTPs had a sludge-treatment process. This shows that only with a given scale of operations the building of a sludge treatment plant would be convenient. A similar deduction can be made by observing the association between size and two other plant characteristics: the type of treatment provided (primary, secondary, or tertiary) and the presence of an activated sludge process (Table 2).

The methods of treatment dominated by physical forces are known as *unit operations*; those dominated by chemical or biological reactions are known as *unit processes*. Unit operations and processes are combined and arranged to provide various levels of treatment known as preliminary, primary, advanced primary, secondary (without or with nutrient removal), and tertiary (advanced) treatment. In preliminary treatment, gross solids such as large objects, rags, and grit are removed to prevent damage to the equipment. In primary treatment, a physical operation (usually sedimentation) is used to remove the floating and settleable materials found in wastewater. For advanced primary treatment, chemicals are added to enhance the removal of suspended solids and to a lesser extent, dissolved solids. In secondary treatment, biological and chemical processes are used to remove most of the organic matter. In tertiary treatment, additional combinations of unit operations and processes are used to remove residual suspended solids and other constituents that are not reduced significantly by conventional secondary treatment. Secondary treatment standards for wastewater are not only concerned with the removal of biodegradable organics, total suspended solids, and pathogens, but also with the removal of nutrients, heavy metals, and priority pollutants (Bonomo, 2008).

Even in these cases, the largest plants were those with better-developed technologies (tertiary and activated sludge), followed by medium and then by small plants that adopted only primary and secondary treatment in 91% of cases and that did not include the use of activated sludge in 19% of observations (Table 2).

Approximately 20% of old plants (built before 1985) received permission from the local authority to derogate from environmental law compared to 2% of mature plants (built between 1985 and 2000), while any new plants (built after 2000) did not receive such authorization. This evidence highlights the effect of the plant's age on the capability of complying with the environmental standards on wastewater outflows.

Table 2. The different features of small, medium and big plants

	Total WWTPs	Sludge treatment plant (yes)	Primary treatment	Secondary treatment	Tertiary treatment	Activated sludge process (yes)
Big (>19000 PE)	10	9	0	8	2	9
Medium (5000<;<19000)	15	9	0	14	1	13
Small (<5000)	114	3	9	104	1	92
	139	21	9	126	4	114

The next table (Table 3) report the estimators calculated by the statistical models. The estimators are grouped into five clusters, according to the items to which they refer: wastewater features, WWTP technology, other features of WWTPs, output variables, and method of sludge disposal. The statistics on total costs are very robust, with an R-squared of 97%, which shows that all clusters exert an effect on the expenditures sustained by a WWTP. In contrast, two-stage DEA models showed a lower R-squared and only those variables categorized as “other features of WWTPs” can affect efficiency.

The estimators must be differently read and interpreted for the total cost function and for the DEA models. In the first case, a positive (negative) sign represents a cost increase (decrease), while for the DEA models a positive (negative) estimator means that efficiency is growing (decreasing) according to an increase in the value of an exogenous variable.

Table 3. The effects of the variables investigated on efficiency

	Total costs function[a]	**Weighted DEA+OLS**	**Weighted DEA+OLS**[b]
	R^2=97.24%	**R^2=31.62%**	**R^2=25.38%**
Wastewater Features			
Non-domestic wastewater (%)	83,424.89**	0.125383	0.1914116
Dilution of wastewater inflow (%)	-59.95848	-0.004311	DNA
Avg. concentration of BOD5 (inflow)	48.05597	0.00038	DNA
Avg. concentration of COD (inflow)	4.270153	-0.000223	DNA
Avg. concentration of N (inflow)	-325.6108	-0.0021	DNA
Avg. concentration of P (inflow)	-554.8456	0.014699	DNA

WWTP Technology			
Type of sewerage system (mixed)	-6,932.18	-0.047075	DNA
Sludge treatment (YES)	152,844.1***	0.093207	-0.0916693
Secondary treatment plant	-22,225.83	0.093207	DNA
Tertiary treatment plant	-33,833.82	0.247644	DNA
Secondary treatment using Activated Sludge	26,068.16	-0.137859	DNA
Secondary treatment using Other	0	DNA	DNA
Aeration system Punctual (P)	37,983.45***	0.045497	DNA
Aeration system widespread (D), none	28,068.21	-0.092033	DNA
Other features of WWTPs			
Distance from WWTP to STP[c]	214.6606	0.00284	DNA
Plant Capacity	-11.7879***	1.56E+00	9.61e-06***
Year of building	661.8202	-0.003188	DNA
PE working capacity/PE potential capacity	-19,408.95*	0.175837**	0.2056044***
Sewerage network served (km)	0.759195	2.08E+00	DNA
Plant authorized with derogation	-37,965.19*	0.139264	0.1838217*
Output Variables			
Removed BOD_5 (kg)	-0.61098		
Removed COD (kg)	-0.0611172		
Removed N (kg)	14.34174***		
Removed sludge (kg)	0.0163052*		
Sludge dry matter (%)	448,766.5*		
Other waste (kg)	0.671111***		
Water treated (m^3)	0.0279786		
Controls not compliant (%)	-135,096.20		
Sludge disposal factors			
Sludge disposed in landfill (%)	-1,756.96	-0.003338	DNA
Sludge to composting plants (%)	-260,831.2**	0.845101	-0.08967
Sludge to agriculture (%)	284,984.6*	-0.415956	DNA

[a] Of operational and environmental variables, [b] Reduced model, [c] Sludge Treatment Plant, DNA = does not apply

*, **, *** Significant at 10 %, 5%, 1%, respectively

Starting from the quality of the wastewater inflows to the plants, only Model (1) showed a significant value, referring to the percentage of water coming from non-domestic customers, such as factories and other activities (i.e., laundries). An increase of 1% in “industrial water” generated an average cost increase of 834 EUR. This result could be explained by considering the high pollutant load of this type of water, meaning that it should be properly treated with specific technologies and reagents, thereby incurring higher costs.

The technologies affecting costs are on-site sludge treatment, which improved costs by more than 1,528 EUR, and the type of aeration. The sludge treatment could be developed by a few simple activities such as dewatering and drying, or alternatively, could be structured in a complex process, that integrates the activities of aerobic or anaerobic digestion. The complex process improves capital and operating expenditures incurred by WWTPs, since it needs new plants and equipment, and more staff, reagents, and energy. At the same time, the strategy of vertical integration generates some benefits in terms of lower costs of sludge disposal, since the waste produced by a well-structured sludge treatment process is less contaminated and easier to be disposed. The results show that the costs are a bit higher than the savings obtained in the disposal stage.

The punctual aeration system improved costs by about 379 EUR (Table 3). The first results demonstrated that, on average, on-site sludge treatment is not convenient. Significant positive effects of these technologies on efficiency were observed when both DEA models were applied. Further research should focus on the benefits derived from innovative technologies, considering only their capability for removal of pollutants from wastewater. The results of Sala-Garrido et al. (2011) that indicated that techno-economic efficiency is optimal for plants with activated sludge process compared with other technologies, are not shown in the current study. The results of this study on the aeration type are partially consistent with those of Hernández-Sancho et al. (2011), which showed that diffuser plants consume more energy than turbine plants.

Only some features of WWTPs actually affect both costs and efficiency (Table 3). Plant capacity, measured in terms of person equivalents, and its degree of usage, exert a positive effect on WWTP management, improving both cost savings and efficiency. The first result is in line with a great part of the results of previous studies (Hernández-Sancho and Sala-Garrido 2009; Molinos-Senante et al. 2014), which demonstrate that larger plants are more efficient than medium and small ones, and that economies of scale affect wastewater treatment processes. Considering all models applied, it is worth underlining that the plant scale affects not only the costs, but also the capability of plants to remove pollutants, since the DEA model includes the quantity of compounds removed among its output variables.

The effects exerted by the percentage of used capacity on costs and efficiency led us to formulate two main implications. First, intensive use of a plant allows for the reduction of costs per cubic meter of wastewater treated and, second, can also facilitate the removal of pollutants.

The last variables observed in this cluster include the option of derogation (ability to release water of quality below environmental standards) provided by the regional local authority. When a WWTP is authorized to exercise derogation, average costs decreased by about 379 EUR and more surprisingly, efficiency went up not only in the volume of wastewater treated, but also in the kilograms of organic matter removed. This implies that a plant exercising derogation can still remove significant quantities of pollutants, so that authorization of not complying with environmental standards might be given when the pollutant loads of the wastewater inflows are particularly high. In any case, the higher efficiency of this type of plants is determined by the low removal rate of pollutants that do not comply with the standards set by law. Since the marginal cost increases more than proportionally with an increase in removal rate, plants in derogation can significantly reduce the costs.

Results referring to the output variables are quite intuitive: the more kilograms of pollutants were removed, the higher the costs were (Table 3). This is confirmed for nitrogen and for other waste and sludge obtained from the treatment process, but not for COD and BOD5 because BOD5, in particular, is removed by microorganisms living in the sludge of the WWTP, which consume a part of the nitrogen to digest the organic matter. While the COD and BOD5 effluent could be completely eliminated in secondary treatment by this process, some part of nitrogen could still remain in the wastewater and an additional expensive process for denitrification would be required.

Finally, the effects of sludge disposal on the efficiency are presented in Table 3. According to the suggestion of a technician in Acque SpA co-operating with authors during this research, the most convenient destination for the sludge disposal would be agricultural land, followed by composting plants, landfills, and incinerators. However, the collected data suggests that the composting plants offer the best alternative. This could be explained by studying the organizational structure of the case studied, where a holding firm owns a company with an operating composting plant. The chain of control allows for relevant synergies, so that the costs for sludge disposal incurred by each plant are conditioned by the transfer prices applied.

6. Conclusions

This study follows two paths to identify the efficiency drivers of wastewater treatment processes: first, regression with OLS to estimate the total costs incurred by 139 WWTPs considering 28 environmental and operational variables, and then a two-stage DEA model with weight restrictions that estimate efficiency by encompassing multiple outputs such as wastewater treated and removed pollutants. Two different issues with these models were discussed: cost efficiency with the OLS and a wider concept of efficiency, which referred not only to the costs but also to the capability of each plant to remove pollutants from wastewater.

Previous studies on this topic have shown that some features of WWTPs, such as plant size, affect efficiency, leading to economies of scale. With reference to technology, treatment with activated sludge is more efficient when technical and economic efficiency is considered, while an aeration system with diffusors consumes more energy than turbines. Finally, previous studies showed that the quantity of pollutants removed was directly proportional to the cost incurred.

The current study confirms prior findings, especially those on the effects exerted by plant size, aeration system, and pollutants removed. Additional findings that refer to the benefits obtained from the full usage of plant capacity and from the option for a facility to be able to deviate from environmental standards at times were also discussed. Advanced technologies (e.g., punctual aeration and sludge treatment on site) were found to negatively affect cost efficiency, while no significant effects were demonstrated when technical efficiency was considered. Moreover, the presence of industrial wastewater and the method of sludge disposal can influence the total plant expenditure.

The variables that appear not to condition costs include the amount of treated water, the quantity of BOD5 and COD removed, the plant age, and the pollutant-concentration in the wastewater.

The identification of those environmental and operational variables affecting WWTP efficiency has its main implications; the provision of guidelines to build a benchmarking tool for comparison of performance of the plants. In fact, once efficiency was measured and a score was assigned to each unit, then the efficiency could be corrected in the light of the effect exerted by exogenous variables, in order to obtain a net score. This would be strictly referred to the real capability of a plant manager to purchase and combine resources for the processes of wastewater treatment.

Moreover, benchmarking tools for comparing the performance of WWTPs can be used by regulators to incentivize the improvement of efficiency by water utilities. This could be done by introducing benchmarking activities into the regulatory action by water authorities.

Further research should focus on these data to better determine the real effect of the abovementioned variables that do not appear to affect efficiency as expected (amount of water treated, pollutant concentrations, BOD5 and COD removed, and plant age). Then, more robust methods should be adopted to better observe the effect of all 28 variables monitored.

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